5th Australasian Congress on Applied Mechanics, ACAM 2007
10-12 December 2007, Brisbane, Australia

Finite Element Thermal Analysis of Conformal Cooling Channels in Injection Moulding

A.B.M. Saifullah [1] and S.H. Masood [1]

[1] *Faculty of Engineering and Industrial Sciences, Swinburne University of Technology, Hawthorn, Melbourne, Australia 3122*

Abstract: The process cycle time in injection moulding process depends greatly on the cooling time of the plastic part, which is facilitated by the cooling channels in the injection mould. Effective cooling channel design in the mould is important because it not only affects cycle time but also the part quality. Traditional cooling channels are normally made of straight drilled holes in the mould, which have limitations in geometric complexity as well as cooling fluid mobility within the injection mould. Over the years, conformal cooling techniques are being introduced as effective alternative to conventional cooling. The main objective of this study is to determine an optimum design for conformal cooling channel of an injection moulded plastic part using finite element analysis and thermal heat transfer analysis. The part cooling time is optimized by conformal cooling channels in the mould using the ANSYS thermal analysis software. Analysis of virtual models showed that those with conformal cooling channels predicted a significant reduction of cycle time with expected improvement in part quality.

Keywords: Cooling channels, conformal cooling, Injection moulding, and thermal analysis.

1 Introduction

Injection moulding is a widely used manufacturing process in the production of plastic parts [1]. Its success depends on the high capability to produce 3D shapes at higher rate than other moulding process. The basic principle of injection moulding is that a solid polymer is molten and injected into a cavity inside a mould which is then cooled and the part is ejected from the machine. Therefore the main phases in an injection moulding process involve filling, cooling and ejection. The cost-effectiveness of the process is mainly dependent on the time spent on the moulding cycle in which the cooling phase is the most significant step. Time spent on cooling cycle determines the rate at which parts are produced. Since in most modern industries, time and costs are strongly linked, the longer is the time to produce parts the more are the costs. A reduction in the time spent on cooling the part would drastically increase the production rate as well as reduce costs. So it is important to understand and optimise the heat transfer process within a typical moulding process.

The rate of the heat exchange between the injected plastic and the mould is a decisive factor in the economical performance of an injection mould. Heat has to be taken away from the plastic material until a stable state has been reached, which permits demolding. The time needed to accomplish this is called cooling time. Proper design of cooling system is necessary for optimum heat transfer process between the melted plastic material and the mould. Historically, this has been achieved by creating several straight holes inside the mould core and cavity then forcing a cooling fluid (i.e. water) to circulate and conduct the excess heat away from the molten plastic. The methods used for producing these holes rely on the conventional machining process such as straight drilling, which is incapable of producing complicated counter-like channels or anything vaguely in 3D space.

An alternative method of cooling system that conforms or fits to the shape of the cavity and core of the mould can provide better heat transfer in injection moulding process, and hence result in optimum cycle time. This alternative method uses contour-like channels of different cross-section, constructed as close as possible to the surface of the mould to increase the heat absorption away from the molten plastic. This ensures that the part is cooled uniformly as well as more efficiently. Now-a-days, with the advent of rapid prototyping technology (e.g. Direct Metal Deposition, Selective Laser Melting) and many advanced computer aided engineering (CAE) software, more efficient cooling channels can be designed and manufactured in the mould with many complex layout and cross-sections.

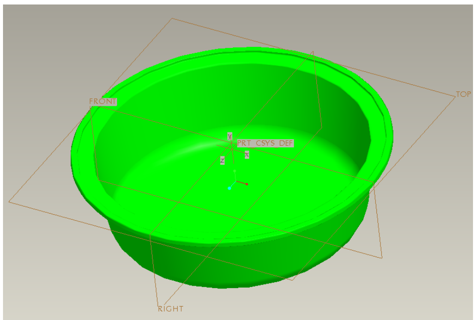
Most of the researches on conventional cooling systems for injection moulding have been directed toward optimal cooling system design to improve the effectiveness and efficiency of cooling. K. M. Au [2] presented a scaffolding architecture for conformal cooling design for rapid plastic injection moulding. Tang et. al. [3] have developed a methodology for optimal design of cooling channels for multi-cavity injection mould in terms of channel size, location and coolant flow rate using finite element analysis for solving the transient heat conduction problem. Li [4] has described a feature based design synthesis approach to develop cooling system design by first decomposing complex part shape into simpler shape elements and then developing an algorithm to generate cooling channels. Lam et. al. [5] have proposed an approach to optimize both cooling channel design and process parameter selection simultaneously through an evolutionary algorithm involving genetic algorithm and CAE.

Research in conformal cooling system has mainly focused on fabrication and testing of prototype conformal cooling moulds using freeform fabrication techniques. Sach et al. [6] described the production of injection moulding tooling with conformal cooling channels using the Three Dimensional Printing (3DP) process. They compared the effectiveness of conformal cooling and conventional cooling of core and cavity by experimental testing and also by finite difference approach. They concluded that the conformal mould was able to maintain a more uniform temperature. Xu et. al. [7] have also studied fabrication of conformal cooling channels using 3DP and proposed a systematic modular approach to design of conformal cooling channels.

This paper presents an investigation on the effects of conformal cooling channel layouts with conventional cooling in an injection mould using the Pro/Engineer and ANSYS thermal analysis (finite element analysis) software and determining which one offers the most effective heat removal.

2 Design of moulds and cooling channels

The part chosen for this study is an injection moulded circular plastic bowl made in polypropylene thermoplastic, as shown in Fig 1(a). The mould of this plastic part consists of a cavity, a core and a stripper. The analysis of the core and stripper mould is presented here though similar results are obtained for the cavity part also.



a)

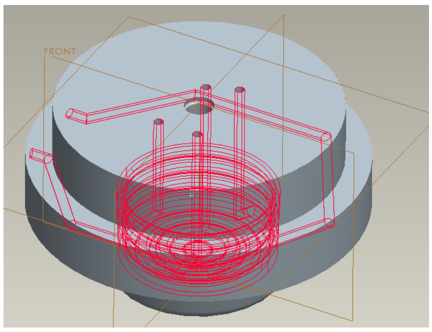


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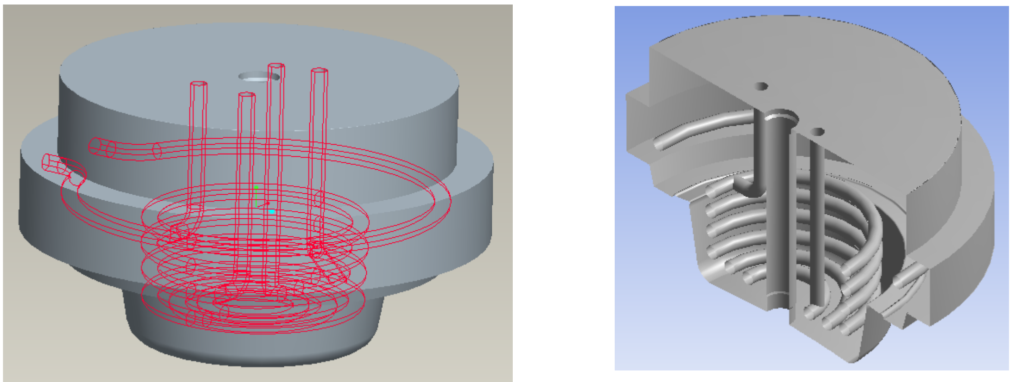
Figure 1: (a) Plastic part (b) 3D model of conventional core and stripper part designed by Pro-E, conventional cooling channels are showing in red lines.

The CAD modelling of the mould and cooling layout design have been done with Pro/Engineer software and the finite element thermal analysis has been done using ANSYS thermal simulation software. Figure1(b) shows 3D CAD model of core and stripper part with conventional cooling channels and Figure 2 shows the CAD model of the core and the conformal cooling channels inside the mould, which have been designed using sweep-cut option. Cooling channels have been designed keeping the design rule of minimum distance between cooling channels and cavity surface as well as channels itself. Diameter of the cooling channels was 12mm.

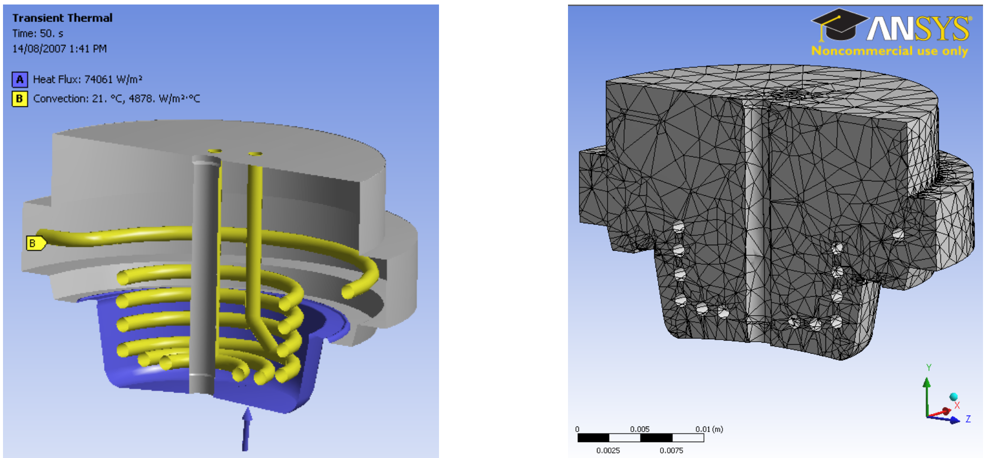


a) b)

Figure 2 :(a) Core and stripper part with conformal cooling channels of circular cross-section (b) Sectional view of the model showing the inside structure.

3 Thermal analysis for cooling channels

ANSYS simulation software has been used for analysis of the parts. By using this advanced module of ANSYS, engineers can easily evaluate product performance by simulating the behaviours of parts and assembly product in thermal loading condition. ANSYS simulation module can perform steady state and transient analysis of a thermal problem. The steady state thermal analysis is used to calculate thermal response to heat loads subject to prescribed temperatures and/or convection conditions. Steady thermal analyses assume a steady state for all thermal loads and boundary conditions. This characteristic is used to test the temperature distribution on the mould surface. Transient thermal analysis is used to calculate thermal responses over the period of time and therefore it is used to estimate the cooling time. After designing cooling channel systems for the injection mould, they need to be evaluated for the efficiency in terms of temperature distribution and cooling time. In this investigation, the thermal analysis for both the core, cavity and stripper moulds were carried out, but this paper will present the thermal analysis of core and stripper part only due to limited space.



a) b)

Figure 3: Sectional view of the mould (a) Boundary condition of transient analysis for conformal cooling channels b) Meshing of the mould.

Both steady-state and transient analysis have been investigated but only transient analysis has been discussed as it gives better range of result than steady-state. From the transient analysis, the thermal response over a period of the time and, therefore, the cooling time can be calculated for the cooling process. Cooling time is the time to remove heat from the melt plastic of 230 °C to the demolding temperature or temperature of the plastic part when it is ejected from the cavities. In the transient analysis, required parameters are temperature of the mould surface which was 230 °C, material was structural steel; type of element (linear tetrahedrons, automatic mesh generation) and the number of node were 48349, 80140 and 43215, 71772 for conventional and conformal channels mould respectively. For boundary condition, the heat flux of 74601 watt/m^2 has been applied in the surface of core that is in contact of melting plastic material. The convection condition is applied to the water lines, and therefore; the convection coefficient was calculated in advance. The heat convection coefficient calculation was based on Dittus-Boetler [8] correction equation (1) for forced convective heat transfer by turbulent flow in a circular pipe and was found to be 4878 watt/m^2 °C.

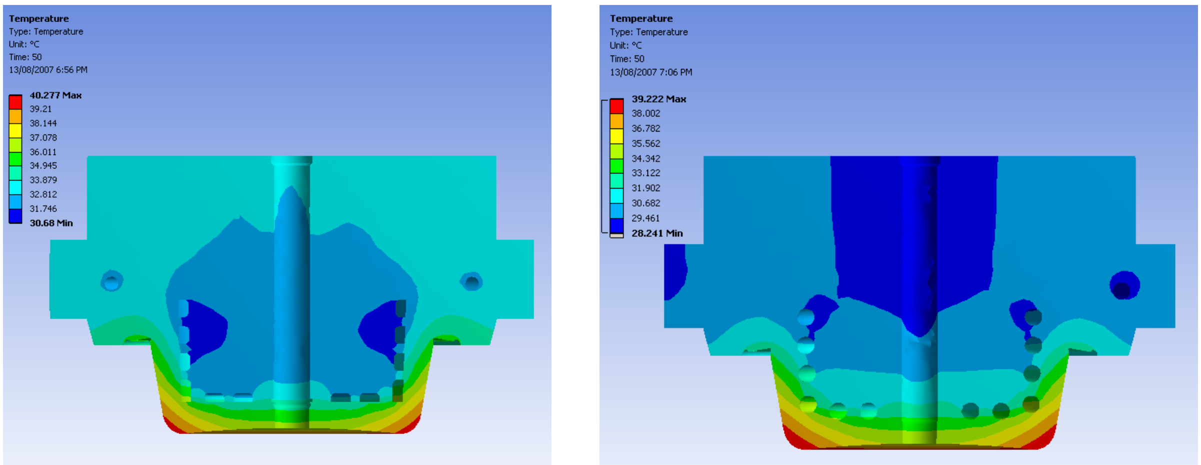
$$h_c = 0.023 \frac{k}{D} \mathrm{Re}^{0.8}\mathrm{Pr}^{0.4} \tag{1}$$

where, h_c = heat transfer co-efficient
k = thermal conductivity of coolant(water)
D = Diameter of the cooling channels
Re = Reynolds Number
Pr = Prandtl Number

The result is shown by a fringe diagram of temperature distribution of different region of the mould and temperature–time graph obtained from transient analysis using ANSYS Thermal simulation software.

4 Result and Discussion

Figure 4 shows the comparative temperature distributions of the analysis result of moulds with conventional and conformal cooling. Figure 4(a) shows the temperature profile of conventional cooling channels mould in which maximum temperature is around 41°C at the surface of the mould that is in contact with the plastic material and the minimum temperature is 32°C which is in the mid region of the mould. On the other hand in Figure 4(b) conformal cooling channels, shows better and uniform temperature distribution. It shows reduced temperature profile of maximum 39 °C to minimum of 28°C.



a)

b)

Figure 4: Temperature distribution of (a) Conventional cooling channel mould b) Conformal cooling channel mould

So from the analysis results, it is noted that conformal cooling channels give better and uniform temperature distribution in the moulding process, which results in optimised heat transfer in injection moulding process.

Another significant result obtained in this study was the cooling time calculation comparison as shown in Figure 5. From Figure 5, it can be shown that conformal cooling channels of circular cross-section give better cooling time than conventional channels. For this particular plastic part, de-moulding temperature is around 55°C. From Figure 5, the demolding temperature for the conventional cooling channels has been found at around 13 second and for the conformal cooling channels it is about at 9 second. So it can be predict that 4 seconds of cooling time can be reduced by applying the conformal cooling channels, which reduced 20% of cycle time.

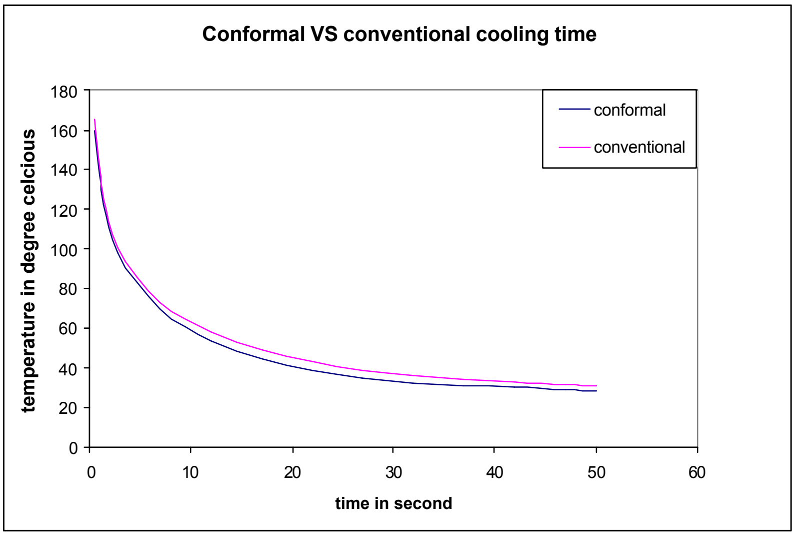


Figure 5: Comparative cooling time plot of conformal and conventional cooling channels mould.

5 Conclusions

The cooling process is one of the most important sub processes in injection moulding because it normally accounts for approximately 80% of the total cycle time and affects directly the shrinkage, bend and warpage of the moulded plastic product. Therefore, designing a good cooling channel system in the mould is crucial since it influences the production rate and quality. The results of ANSYS thermal simulation have shown that with proper geometry sections and proper layout designs, the conformal cooling channels can obtain up to 20% reduction in cooling time, thus greatly improving the production rate and the production quality of injection moulded parts. In this paper analysis result of only core and stripper part has been shown, but similar reduced cycle time and uniform temperature distribution of the full assembly of injection mould have been observed using conformal cooling channels.

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